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**PHYSICS AND EVOLUTION OF  
OBSCURED X-RAY SOURCES:  
A MULTIWAVELENGTH APPROACH**

Tesi di dottorato di

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DOTTORATO DI RICERCA IN ASTRONOMIA

XVI CICLO [2000–2003]



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# Introduction

One of the primary goals of observational cosmology is to trace star formation and nuclear activity along with the mass assembly history of galaxies as a function of redshift and environment. Theoretical arguments suggest that there is a fundamental link between the assembly of Black Holes and the formation of spheroids in galaxy halos. The tight relation observed in local galaxies between the black holes mass and the velocity dispersion (the  $M_{\text{BH}}-\sigma$  relation) and the fact that the locally inferred black hole mass density appears to be broadly consistent with the mass accreted during the quasar phase further support the idea that the nuclear activity, the growth of the black holes and spheroid formation are all closely linked. Thus, it is clear that a detailed investigation of the formation and evolution of Active Galactic Nuclei (AGN) over a wide range of redshifts, and the comparison with galaxy evolution, could provide information about the link between nuclear activity, star formation and the galaxy assembly that seem to co-exist in the early Universe. In this framework, the hard X-ray band is by far the cleanest one where to study the history of accretion in the Universe, being the only band in which accretion processes dominate the cosmic background.

## The X-ray background

The cosmic X-ray background (XRB) was discovered at the dawn of the X-ray astronomy: during the first successful rocket flight launched to study the X-ray emission from the Moon, the presence of a residual diffuse emission was also “serendipitously” revealed (Giacconi et al. 1962). The lack of any correlation with the galactic latitude, and a dipole anisotropy consistent with that of the dipole component of the Cosmic Microwave Background (CMB; Shafer & Fabian 1983) strongly argued from the beginning in favour of a cosmological origin of this extragalactic background radiation.

The first broad-band measurements of the XRB spectrum was obtained at the end of the 70's with the HEAO-1 satellite. Marshall et al. (1980) showed that the HEAO-1 data were very well fitted by a 40 keV thin thermal bremsstrahlung model, approximated below 15 keV with a simple power-law spectral function ( $F(E) \propto E^{-\Gamma}$ ) with photon index  $\Gamma \sim 1.4$ . It was therefore quite natural to hypothesize the presence of a truly diffuse hot Inter Galactic Medium (IGM) with a characteristic temperature of  $kT=40(1+z)$  keV, as

originally proposed by Field and Perrenod (1977).

However, a reasonable extrapolation of the X-ray properties and optical counts of extragalactic sources led to the conclusion that discrete sources could contribute significantly to the XRB (Schmidt & Green 1986). Moreover, Giacconi & Zamorani (1987) have subsequently shown that, once the contribution estimated from known AGN is removed, the residual background spectrum is too flat to be interpreted in terms of an optically thin bremsstrahlung from a diffuse IGM.

This hypothesis has been then entirely discarded with the results from the COBE satellite (Mather et al. 1990). A diffuse, hot ( $T \gtrsim 10^8$  K) IGM should give rise to evident high-frequency distortions in the CMB spectrum through inverse-Compton scattering, which have not been observed by COBE; this implies that the contribution of hot gas to the XRB is lower than 0.01% (Wright et al. 1994).

As a consequence, the only viable alternative for the XRB origin remained the superposition of discrete sources, and the most likely candidates appeared immediately to be AGN.

The most serious problem with the discrete-source origin for the XRB remained the so-called “spectral paradox” (Boldt 1987): at that time there were already stringent evidences that the AGN X-ray continuum in the 2–10 keV band is well described by a power-law with index  $\Gamma \simeq 1.7$ –1.9 (Mushotzky et al. 1984; Turner & Pounds 1989), too soft to fit the value observed for the hard XRB in the same energy band ( $\Gamma \sim 1.4$ ).

Setti & Woltjer (1989) showed that, on the basis of Unification Schemes of AGN, strong X-ray absorption is naturally predicted for the sources optically classified as narrow line, Type 2 objects\*, and that the amount of obscuring matter along the line of sight, measured in equivalent neutral hydrogen column ( $N_H$ ), can be even in excess than  $10^{24} \text{ cm}^{-2}$ . As a consequence, the resulting X-ray spectra will peak at high energies (from a few keV up to  $\gtrsim 10$  keV, depending from the  $N_H$ ) and the net result is a flatter power-law spectral index. The “spectral paradox” could be therefore theoretically solved by assuming that the XRB is due to the superposition of absorbed and unabsorbed objects, with the same intrinsic steep ( $\Gamma \sim 1.8$ ) power-law continuum.

Following these indications, several authors have refined and developed population-synthesis models able to reproduce the XRB spectral shape and intensity (e.g. Madau, Ghisellini & Fabian 1994; Comastri et al. 1995, 2001; Gilli, Salvati & Hasinger 2001), assuming a wide range of redshifts (i.e. evolution) and column densities† of the absorbing matter in the range

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\*In the zero-th order Unification Schemes, there is a correspondence between X-ray and optical absorption: Type 2 narrow-lined objects are X-ray obscured, and Type 1 broad-lined objects are not. The underlying continuum is intrinsically the same, and the differences in the optical and X-ray spectra are only due to orientation effects (e.g. Antonucci 1993).

†If the X-ray obscuring matter has a column density which is equal or larger than the inverse of the Thomson cross-section ( $N_H \geq \sigma_T^{-1} \simeq 1.5 \times 10^{24} \text{ cm}^{-2}$ ) the source is called, by definition, “Compton Thick”.

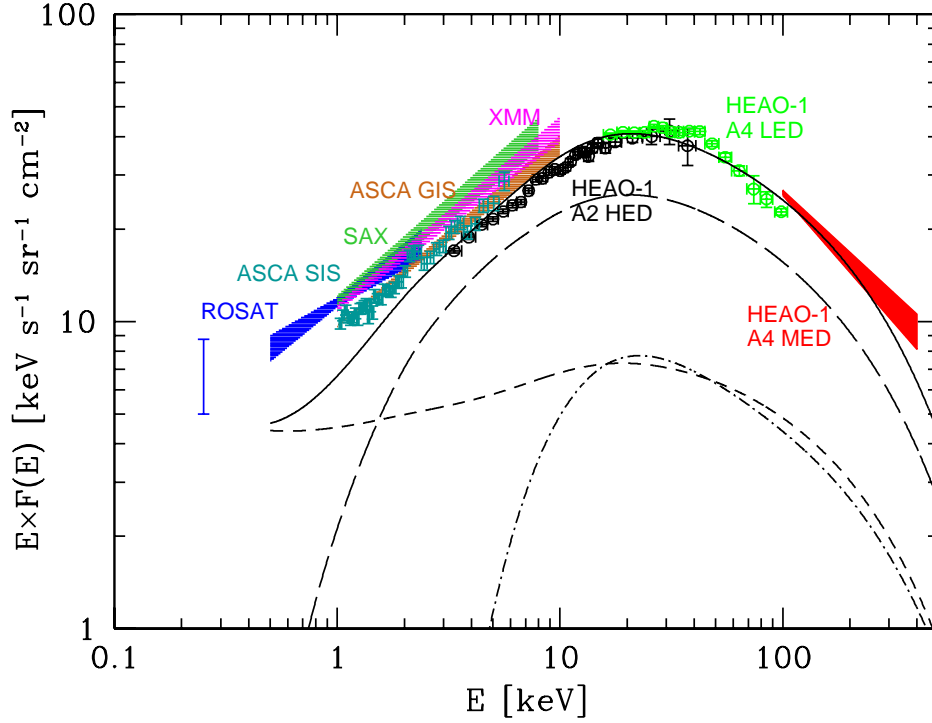


Figure 1.1 The AGN contribution (solid line) to the XRB spectral energy density as measured by different instruments (labeled). The contribution of unobscured ( $N_H < 10^{21} \text{ cm}^{-2}$ , dashed line), Compton thin ( $N_H = 10^{21} - 10^{24} \text{ cm}^{-2}$ , long-dashed line) and Compton thick ( $N_H > 10^{24} \text{ cm}^{-2}$ , dot-dashed line) AGN is also shown. [From Comastri (2004)].

$N_H = 10^{21} - 10^{25} \text{ cm}^{-2}$ . In Fig. 1.1 a compilation of XRB measurements in different energy bands is shown along with the best-fit model from Comastri et al. (2001). The contribution of unobscured (dashed line), mildly obscured ( $N_H = 10^{21} - 10^{24} \text{ cm}^{-2}$ , Compton Thin) and heavily obscured ( $N_H > 10^{24} \text{ cm}^{-2}$ , Compton Thick) sources is also reported.

The combined fit of other observational constraints in addition to the XRB spectral shape (in primis the number counts, and the redshift and absorption distributions in different energy ranges) is needed to build a self-consistent model and discriminate among the assumptions adopted for the cosmological evolution of the discrete sources. In particular, the key parameter turned out to be the evolution of obscured (Type 2) sources. As an example, the baseline AGN synthesis model adopt a simple Pure Luminosity Evolution (PLE) and is based on the zero-th order AGN Unification Schemes (Antonucci

1993); this implies that 1) the evolution of obscured AGN is *assumed* to follow that of unobscured AGN, and 2) the existence of a population of high-luminosity, highly obscured quasars (the so-called QSO2) is *naturally* postulated (Comastri et al. 1995). Indeed, it has been subsequently shown that QSO2 are *necessary* in reproducing the 2–10 keV source counts at relatively bright fluxes ( $\simeq 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ ; Gilli et al. 2001; Comastri et al. 2001); however, despite intensive optical searches, these narrow-line high-redshift objects appear to be elusive, suggesting a space density and evolution different from that expected from unified schemes and calling for substantial revisions of the main assumptions of XRB baseline models.

## Hard X-ray surveys and “new” observational constraints

A large number of multiwavelength projects have been specifically designed in the last years to investigate the evolutionary properties of AGN.

The results from hard X-ray surveys carried out at the end of the 90’s with ASCA (e.g. the ASCA GIS survey, Cagnoni et al. 1998; the ASCA MSS and LSS Surveys, Ueda et al. 1999; Akiyama et al. 2002) and BeppoSAX (the BeppoSAX HELLAS survey, Fiore et al. 2001; Vignali 2001) constituted the first piece of evidence that AGN synthesis models do indeed work. However, the resolved fraction of the XRB was still too low ( $\sim 25 - 30\%$ ) to quantitatively constrain all the models parameters; in particular, sampling the bright X-ray fluxes ( $> 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ ) previous X-ray surveys were strongly biased towards luminous, high-redshift sources.

The superb capabilities of the detectors on-board the *Chandra* and XMM-*Newton* X-ray satellites have opened up new frontiers in testing these predictions down to limiting fluxes where the entire spectral energy density in the 2–10 keV band is expected to be resolved. Thanks to the deep X-ray surveys carried out in the *Chandra* Deep Field North (CDFN, Brandt et al. 2001a, Alexander et al. 2003), *Chandra* Deep Field South (CDFS, Giacconi et al. 2001) and the Lockman Hole (Hasinger et al. 2001) the X-ray sky is now probed down to a 2–10 keV flux limit of about  $2 \times 10^{-16}$  erg cm $^{-2}$  s $^{-1}$  and a fraction as large as 80-90% of the diffuse XRB is resolved into discrete sources (Mushotzky et al. 2000; Hasinger et al. 2001; Rosati et al. 2002; Alexander et al. 2003), the bigger uncertainty being the XRB normalization (Barcons, Mateos, & Ceballos 2000).

Moreover, hard X-ray surveys have proven to be very efficient to uncover obscured accreting black holes, confirming, at least qualitatively, the predictions of standard models, in which the 2-10 keV XRB is mostly made by the superposition of obscured and unobscured AGN. In particular, the recent findings are in very good agreement with the main predictions of XRB synthesis models for the source counts in different X-ray bands (see Moretti et al. 2003 for a comprehensive compilation of recent data); moreover, the observed average spectrum of the sources detected down to  $10^{-16}$  erg cm $^{-2}$  s $^{-1}$  now exactly matches that of the XRB ( $\langle \Gamma \rangle \sim 1.4$ , Tozzi et



al. 2001a,b).

Deep, pencil beam surveys, albeit extremely important, explore only a limited region of the luminosity–redshift plane, being strongly biased against the brightest (and rare) objects. Sizable samples of objects detected at the bright X–ray fluxes ( $\gtrsim 10^{-14}$  erg cm $^{-2}$  s $^{-1}$ ) over an area of the order of a few square degrees are needed to homogeneously cover the Hubble diagram and to obtain a well–constrained luminosity function with a similar number of sources per luminosity decade and per redshift bin. The detailed study of the nature of the hard X–ray source population, is indeed pursued complementing deep pencil beam observations with shallower, larger area surveys. In the last few years several projects with both *Chandra* and XMM–*Newton* have already started, with the aim of surveying from few to several tens degrees of the hard X–ray sky at different limiting fluxes (i.e. HELLAS2XMM – Baldi et al. 2002; Champ – Green et al. 2004; SEXSI – Harrison et al. 2003; XMM HBS – Caccianiga et al. 2004). The main goal of these projects is to collect a statistically significant number ( $\sim 200$ ) of X–ray, absorbed sources (including the “rare” QSO2) that will be used to derive the luminosity function of obscured objects that is nowadays basically unconstrained.

## Redshift and absorption distributions

Although quite successful in reproducing the XRB spectral shape, intensity and X–ray number counts, AGN synthesis models, at least in their simplest version (where the evolution of the obscured population is assumed to be the same as that of unobscured quasars), do not reproduce other observational constraints, as the observed redshift and absorption distributions.

There are increasing evidences (Hasinger 2003; Barger et al. 2003) that the bulk of the XRB appears to be produced at relatively low redshift ( $z < 1$ ) and dominated by relatively low luminosity Seyfert galaxies ( $L_X = 10^{42} - 10^{44}$  erg s $^{-1}$ ) rather than mainly due to luminous quasars at higher redshift ( $z=1.5-2$ ), as observed by previous shallower ROSAT and ASCA surveys and predicted by XRB synthesis models.

In the left panel of Fig. 1.2 (from Hasinger 2003) the predictions from the Gilli et al. (2001) model are compared with the redshift distribution of AGN selected from the CDFN and CDFS samples. At redshift below  $z=1.5$ , predicted and observed distributions differ drastically, definitively indicating that the evolution of obscured sources is not as simple as postulated.

Another important observational constraint that can be used to test the assumptions of the XRB models is the number of obscured (e.g.  $N_H > 10^{22}$  cm $^{-2}$ ) sources as a function of the X–ray flux. While standard model predictions are able to *qualitatively* explain the hardening of the average spectrum of X–ray sources with decreasing flux, the rather steep hardening observed in both the CDFN and CDFS observations (Tozzi et al. 2001; Piconcelli et al. 2003) is a further indication that the evolution cannot be as simple as initially postulated. Moreover, preliminary results from X–ray spectral analysis on the fraction of obscured ( $N_H > 10^{22}$  cm $^{-2}$ ) sources indicate that observations fall short by a factor of  $\sim 2$  with respect to current

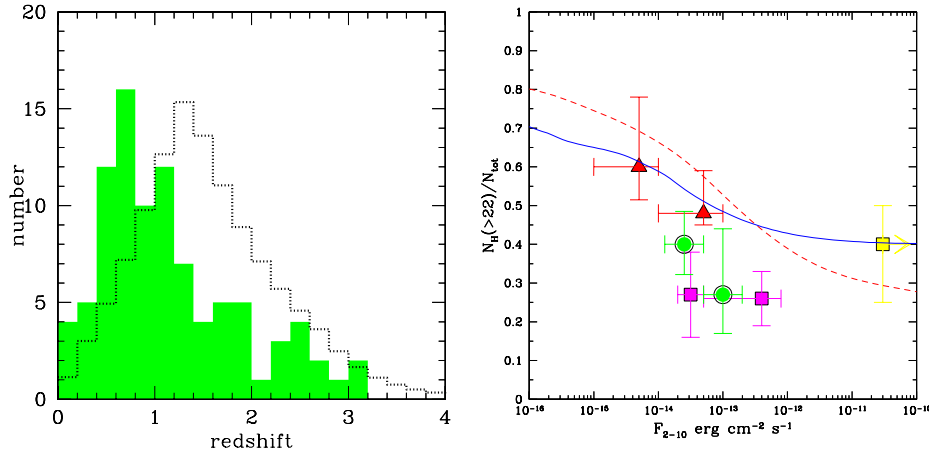


Figure 1.2 *Left*: Redshift distribution for a selected sample of 93 X-ray sources with  $f_{2-10} > 5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the central regions of the CDFS, CDFN, Lockman Hole, Lynx field, and SSA13 field (see Gilli 2003 for details). The data (shaded area) are compared with the predictions of Gilli et al. (2001) at the same limiting flux (dotted line). [From Hasinger (2003)].

*Right*: The expected fraction of objects with absorption column densities larger than  $10^{22} \text{ cm}^{-2}$  as a function of the 2–10 keV for the Comastri et al. 1995 model (solid line) and the Gilli et al. 2001 model (dashed line). The Comastri et al. 1995 model has been normalized to the observed fraction of absorbed sources in the HEAO1–A2 AGN sample of Piccinotti et al. 1982 (*filled square* at bright fluxes). The other points and associated error bars correspond to the values found by Picconcelli et al. (2003, *filled squares*) and those obtained by Perola et al. (2004, *filled circles*), both derived from proper X-ray spectral analysis. The *filled triangles* at the faintest fluxes refer to the CDFN data (Brandt et al. 2001a; Barger et al. 2002) and have been derived from the observed hardness ratio assuming  $\Gamma = 1.7$ , and the redshift proper of the source if it is available, or  $z = 1$  otherwise.

model predictions at relatively bright X-ray fluxes ( $\gtrsim 10^{-14}$ , Picconcelli et al. 2003; Perola et al. 2004), while a much better agreement between data and predictions seems to occur at fainter fluxes, using the hardness-ratio technique (Fig. 1.2, right panel). Finally, there are also evidences that the obscuration could be dependent from the source luminosity and redshift (Ueda et al. 2003).

All the findings discussed above constitute robust evidences for a luminosity dependence in the number density evolution of X-ray selected AGN, already pointed out by previous soft (ROSAT, Miyaji et al. 2000) and hard (*BeppoSAX*, La Franca et al. 2002) X-ray surveys. Cowie et al. (2003) and Hasinger (2003) calculated preliminary luminosity functions (LF) on the basis of the results from the deep surveys. The shape of the LFs in different redshift shells is significantly different so that the cosmological evolution can be described neither by pure luminosity nor pure density evolution. The

most surprising result is, however, that lower luminosity AGN show much less or even negative density evolution with respect to the strong positive evolution observed for relatively luminous QSO. The observed evolution for the low-luminosity population (a very rapid increase of volume emissivity at low redshift) can explain the sharp peak observed at  $z \sim 0.7 - 0.8$  in the deep fields (Hasinger 2003).

Interestingly enough, the late evolution of the low-luminosity AGN is very similar to that required to explain the steep slope of the observed 15 micron number counts (Franceschini et al. 2001). Given the rather strong indications that the 15 micron emission is mainly due to dust enshrouded stellar activity (rather than AGN), a similar evolution of hard X-ray and MIR selected sources adds further strength to a close connection between the onset and fueling of AGN activity and star formation. On this basis, Franceschini et al. (2002) and Gandhi & Fabian (2003) elaborated XRB synthesis models able to reproduce the observed peak at  $z \sim 0.7$  in the redshift distribution, assuming that Type 1 AGN are distributed according to the well-determined soft X-ray luminosity function (Miyaji, Hasinger & Schmidt 2000), and that the evolution of Type 2 AGN follows the MIR one. However, as convincingly demonstrated by Gilli (2003), both these models are in disagreement with another observational constraint, the ratio of Type2/Type1 object as a function of redshift.

Although converging to the same bottom line (a luminosity-dependent cosmological evolution), the results on the space density and evolution suffer from substantial spectroscopic incompleteness and therefore have still to be taken with a grain of salt. Indeed, at the faintest fluxes explored by the CDFN and CDFS optical counterparts are sometimes so faint to prevent redshift measurements (even photometric) with the largest ground-based facilities; as a result, the spectroscopic completeness is only  $\sim 50 - 60\%$  (Barger et al. 2003; Szokoly et al. 2004). This limitation mainly affects the study of the evolution of high-redshift objects.

## The $f_X/f_{opt}$ diagnostic

It is well known (Maccacaro et al. 1988) that various classes of X-ray emitters are characterized by different values of their X-ray-to-optical flux ratios (hereinafter X/O) and the observed X/O can yield important information on the nature of X-ray sources.

For a given X-ray energy range and R-band magnitude the following relation holds:

$$\log X/O = \log f_X + R/2.5 + const \quad (1.1)$$

where  $f_X$  is the X-ray flux,  $R$  is the optical magnitude and *const* depends only on the R-band filter used in the optical observations<sup>‡</sup>. A value of

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<sup>‡</sup>For the most popular R-band filters,  $\Delta const \leq 0.2$ ; an indicative, average value is

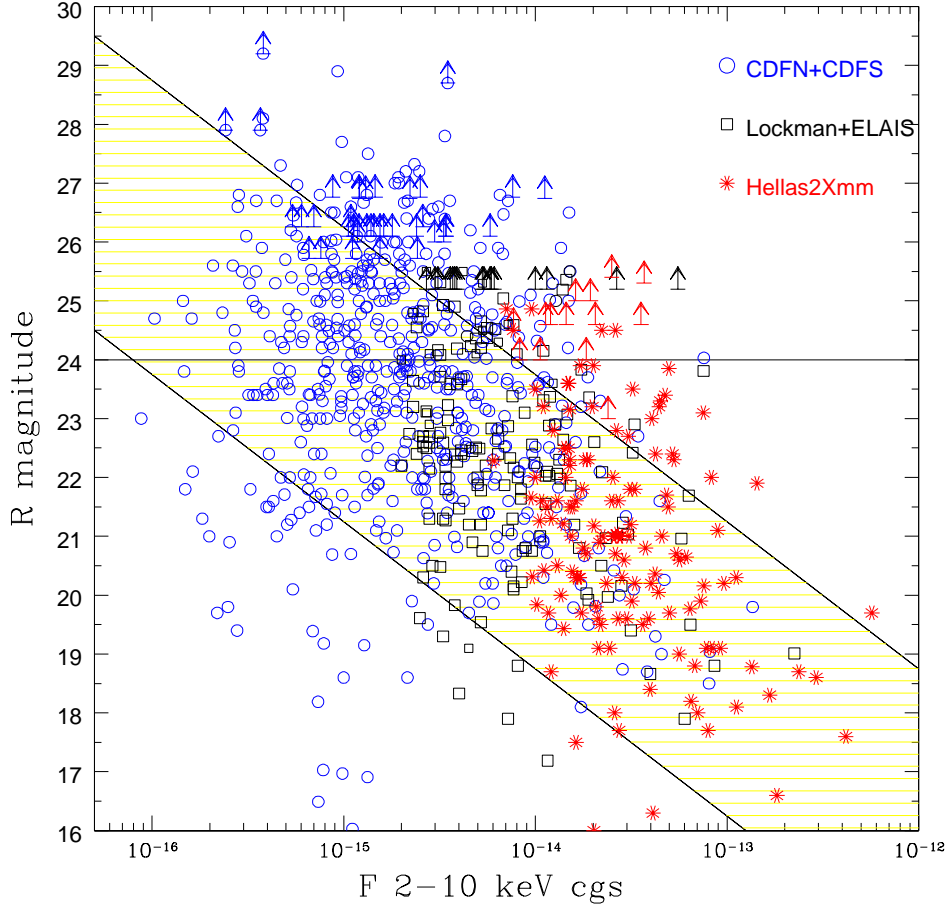


Figure 1.3 The 2–10 keV flux versus the R band magnitude for five different hard X-ray surveys. From bright to faint X-ray fluxes: *asterisks* mark the HELLAS2XMM sources (this PhD Thesis); *squares* refer to the sources in the Lockman Hole XMM–Newton observation (Mainieri et al. 2002) and in the ELAIS deep *Chandra* survey (Manners et al. 2003); *circles* mark the sources detected in the *Chandra* Deep Field South (Giacconi et al. 2002) and in the *Chandra* Deep Field North (Alexander et al. 2003; Barger et al. 2003). The shaded area represents the region occupied by known AGN (e.g. quasars, Seyferts, emission line galaxies) along the correlation  $\log(X/O) = 0 \pm 1$ . The horizontal straight line at  $R=24$  represent a conservative limit for spectroscopic observations.

$-1 < \log(X/O) < 1$  is a clear sign of AGN activity, since the majority of spectroscopically identified AGN in both ROSAT (e.g. Hasinger et al. 1998; Lehmann et al. 2001) and ASCA (Akiyama et al. 2000) surveys fall within this range, while normal galaxies and stars usually have lower ( $\log(X/O) < -2$ ) values.

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$const=5.5$  (see Hornschemeier et al. 2000) and it can be used when datasets from different observations are compared.

The optical identification of sources discovered in deep and medium deep *Chandra* and XMM-*Newton* surveys confirms this trend to fainter X-ray fluxes and, at the same time, show evidence of a relatively large number of sources which deviate from  $\log(X/O) = 0 \pm 1$  (Fig. 1.3). Indeed, the range of X/O now spanned by X-ray selected sources is extremely large, up to 6 dex or even more. Most important, an interesting new population of X-ray sources characterized by values of their  $X/O > 10$  (i.e. sources that are optically weak with respect to the observed X-ray flux) is present in both deep and shallow surveys, and its fraction seems to be constant ( $\sim 20\%$ ) over  $\sim 3$  decades of fluxes.

Almost by definition, sources with  $X/O > 10$  have faint optical magnitudes. For example, a 2–8 keV flux of  $10^{-15}$  ( $10^{-16}$ )  $\text{erg cm}^{-2} \text{s}^{-1}$  and an  $X/O=10$  correspond to  $R$  magnitudes  $\sim 25.5$  ( $\sim 28$ ), challenging (well beyond) the spectroscopic capabilities of 10m-class telescopes.

In this respect it is important to note that shallow, hard X-ray surveys, designed to sample relatively bright X-ray and optical fluxes, are best suited to investigate the nature of sources with high X/O: at fluxes of the order  $10^{-14} - 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$ , the magnitudes of the optical counterparts of high X/O sources are of the order of  $R \simeq 24$  or brighter, making spectroscopic follow-up observations feasible.

It seems reasonable to argue that most of the sources characterized by high X/O are high redshift, obscured AGN. If this were the case, they could contribute to reduce the disagreement between the redshift distribution predicted by XRB synthesis models and that observed in deep *Chandra* and XMM-*Newton* fields (Hasinger 2003; Gilli 2003), and provide an important contribution to the total energy density of the background light.

## Black Hole demography

An important piece of observational evidence on how supermassive black holes (SMBHs) have assembled comes from the demography of the AGN population.

The tight correlation observed between the black hole mass and velocity dispersion of galactic bulges (the  $M_{\bullet}-\sigma$  relation, Gebhardt et al. 2000; Ferrarese & Merritt 2000) is generally taken as strong evidence that the growth of SMBH and the formation of galaxies go hand in hand (see, e.g., Ho 2004). The first implication of this relation is that most (if not all) galactic bulges contain “dormant” SMBHs. If this is the case, the observed local black hole mass density ( $\rho_{\bullet}$ ) should be explained in terms of the overall black hole mass density accreted in the AGN phase. The BH mass density due to AGN can be estimated from the observed radiation( $S$ ) emitted by active black holes in a given energy band over the cosmic time, using the elegant Soltan’s argument (Soltan 1982):

$$\rho_{\bullet} = \frac{1}{\eta c^2} \frac{4\pi k_{bol}}{c} (1 + \langle z \rangle) \int S \frac{dn}{ds} dS. \quad (1.2)$$

that, besides the knowledge of the differential counts ( $\frac{dn}{dS}$ ) and of the average redshift of the peak of AGN activity ( $\langle z \rangle$ ), requires *assumptions* about the efficiency ( $\eta$ ) of turning accreted rest-mass energy into radiated energy, and the bolometric correction ( $k_{bol}$ ) which relates the total emissivity to the emissivity in the chosen band.

Hard X-ray surveys have already probed the largest fraction of the whole AGN population; this makes the results obtained from both deep and shallow surveys the most suitable to estimate the *total* black hole mass density due to accretion. Moreover, given that the XRB spectral intensity records the bulk of the accretion power, the integral in Equation 1.2 can be rewritten:

$$\rho_{\bullet} = \frac{1}{\eta c^2} \frac{4\pi k_{bol}}{c} (1 + \langle z \rangle) I_0 \quad (1.3)$$

where  $\langle z \rangle$  is the average redshift of the X-ray sources detected in the 2–10 keV band and  $I_0$  is the absorption corrected XRB intensity in the same energy band.

Early estimates, made assuming the same evolution for obscured and unobscured sources (e.g.  $\langle z \rangle = 2$  observed for soft X-ray selected QSO) and coupled with the evidences that more than 80% of the accretion is obscured, led to a  $\rho_{\bullet} = 6 \div 17 \times 10^5 \text{ M}_{\odot} \text{ Mpc}^{-3}$ , if a standard  $\eta = 0.1$  is adopted (Fabian & Iwasawa 1999; Elvis, Risaliti & Zamorani 2002).

With the data on hard X-ray selected active SMBHs rapidly accumulating, a lower value for  $\rho_{\bullet}$  from AGN appears more plausible (see Fabian 2003 for a recent review). Moreover, now it is possible to safely (e.g. with the lowest number of arbitrary assumptions) compare the black hole mass density expected from the AGN activity with that observed in nearby galactic bulges (e.g. Haehnelt 2003).

## Do Unified Schemes work?

As already shown, current synthesis models, built on a strictly X-ray based scheme, are far from being unique (see Comastri 2001 for a review); in particular, a simultaneous fit to all the observational constraints requires *at least* to relax some of the key assumptions in Unified Schemes. Moreover, the broad band Spectral Energy Distribution (SED) of the XRB constituents, outside the X-ray domain, is essentially unconstrained, with the consequent lack of model predictive power at longer wavelengths. In this respect it is not surprising that the results of multi-wavelength follow-up from both shallow and deep surveys, have started to unveil that the sources responsible for a large fraction of the XRB energy density are characterized by broad band properties which are significantly different from those of AGN selected in the optical and soft X-ray bands (Barger et al. 2002, Giacconi et al. 2002; Willott et al. 2003). Although there are compelling theoretical and observational evidences which suggest that the large majority of the hard X-ray sources are obscured AGN, the origin of such a broad variety in their

multiwavelength properties is still far to be understood.

On the one hand, there is rather increasing evidence of the presence of luminous X-ray sources in the nuclei of galaxies without any evidence of optical nuclear activity nor of a high star formation rate in their optical spectra, which are instead typical of early-type “normal” galaxies (Hornschemeier et al. 2001; Giacconi et al. 2001; Barger et al. 2001; Comastri et al. 2002a,b). Moreover, there are evidences that the one-to-one relation postulated in Unified schemes between optical Type 1 and X-ray unobscured sources, and between optical Type 2 and X-ray obscured sources, does not hold especially at high redshifts and luminosities (Brusa et al. 2003; Page et al. 2003).

On the other hand, the hard X-ray selection turned out to be very efficient in revealing an AGN population with optical to near-infrared colours redder than those of optically selected QSOs. In this respect, the discovery that a sizable fraction of hard X-ray sources are also associated to extremely red objects (EROs) with optical to near-infrared colour  $R-K > 5$  (Lehmann et al. 2001; Mainieri et al. 2002; Alexander et al. 2002) is even more intriguing. The observed optical to near-infrared colors of EROs are consistent with both passively evolving elliptical galaxies at  $z \sim 1$  or with dust reddened starburst galaxies and obscured AGN. Given the key role played by this class of objects to constrain models for the formation and evolution of massive elliptical galaxies and star formation at high redshift, X-ray observations of those objects provide an exciting opportunity to investigate the link between galaxies and AGN evolution.





# The goals of this PhD Thesis

The main goal of the present work is to provide further contributions to the understanding of the physical and evolutionary properties of AGN, which are necessary to derive the accretion history of super massive black holes that reside in most of galaxies.

In order to make significant progress in this direction the following issues will be addressed:

- A) What is the nature and luminosity/redshift dependence of sources which seem to deviate from the simplest version of unified models? How many are they?
- B) What is the nature of X-ray bright optically faint sources? What is their redshift? Are they highly obscured, high redshift AGN?
- C) Which is the evolution of hard X-ray sources? Is the evolution of low-luminosity AGN different from that of high-luminosity AGN? Is the relic Black Hole mass density accreted in the active phase consistent with the local one?
- D) What are the optical/IR colors of obscured hard X-ray sources? How many hard X-ray sources are extremely red objects (EROs)? Conversely, what are the high energies properties of the near-infrared selected ERO population? How many infrared selected EROs are X-ray emitters?

Observations at high energies yield important information on the structure and nature of AGN; when coupled with deep optical and near-infrared (photometric and spectroscopic) follow-up, they provide constraints on the mass of the growing black holes and, therefore, are essential to better understand the nature of the various components of the X-ray background light and can be used as test for the accretion paradigm. In this framework, we have started a program of multiwavelength follow-up observations of hard X-ray selected sources serendipitously discovered in XMM-*Newton* fields over  $\sim 4 \text{ deg}^2$  (the HELLAS2XMM survey; Baldi et al. 2002).

Conversely, optical and near-infrared surveys of galaxies are crucial to discriminate between different cosmological scenarios (e.g. hierarchical or monolithic growth of the structures) and, thus, to recover the galaxy

evolution path. With a complementary approach to that of hard X-ray surveys, in order to investigate the link between nuclear activity and the galaxy formation, XMM-*Newton* and *Chandra* observations of photometric and spectroscopically selected EROs have been obtained.

The HELLAS2XMM survey will be described in Chapter 1, with particular emphasis on the multiwavelength data obtained for the sources detected in  $\sim 1 \text{ deg}^2$ , and on the importance of high spatial resolution observation in the optical identification process of hard X-ray sources counterparts.

In Chapter 2 I will present the multiwavelength properties of hard X-ray sources, as revealed from optical and X-ray spectroscopy of the brightest population responsible for the XRB energy density. In particular, I will focus the discussion on those sources which seem to deviate from the simplest version of unified models.

In Chapter 3 I will present spectroscopic identifications and near-infrared analysis of objects with high X/O selected in the HELLAS2XMM survey. I will also present different approaches developed to estimate the redshift of optically faint X-ray sources and needed to build an almost “complete” sample of hard X-ray selected sources.

In Chapter 4 the results from the HELLAS2XMM survey, complemented with those obtained from the deep surveys, will be used to derive the number and luminosity densities as a function of redshift. Observational constraints for the cosmic evolution, the integrated black hole mass density and the QSO2 will also be discussed.

In Chapter 5 the X-ray and optical properties of X-ray detected EROs from a large and complete near-infrared sample are presented, and compared with those of hard X-ray sources with similar R-K colors and QSO2. A selection criterion to pick up QSO2 on the basis of the observed optical, near-infrared and X-ray fluxes is proposed.

As a comparison with the results on X-ray detected EROs, in Chapter 6 the average high-energy properties of non-AGN EROs are investigated through the “stacking analysis” technique, and the existence of a dichotomy in the spectroscopic classification is confirmed also in the X-rays.

Finally, in the last Chapter, I will summarize the most important results of the present work and I will briefly discuss the implications for future observations. I will assume a  $\Lambda$ CDM cosmology, with the following values for the Hubble constant and the cosmological parameters:  $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_\Lambda=0.7$ ,  $\Omega_m=0.3$  (Spergel et al. 2003).

# Conclusions

The most important results obtained in this PhD Thesis concern the physical and evolutionary properties of obscured AGN detected in hard X-ray surveys, that contributes most to the accretion history in the Universe.

- The HELLAS2XMM survey has provided optical identifications and spectroscopic classifications for 97 out of 122 hard X-ray selected sources detected in  $\sim 1 \text{ deg}^2$  (the HELLAS2XMM 1dF sample). The spectroscopic completeness of the sample ( $\sim 80\%$ , mainly limited by the faintness of the optical counterparts) is one of the highest for sources detected at flux level  $\gtrsim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  and the results from the HELLAS2XMM survey represent a complementary and necessary probe of the hard X-ray sky with respect to the deep, pencil-beam *Chandra* and XMM-*Newton* surveys.

A detailed study of one specific field (the PKS 0312-77 field) for which *Chandra*, radio and near-infrared data were also available, has clearly demonstrated the need for high spatial resolution observations to exactly identify the hard X-ray sources counterparts (Chapter 1).

- The overall picture emerging from the optical identifications of the HELLAS2XMM 1dF sample indicate a wide spread in the optical (both in the continuum shape and emission lines) and X-ray properties of the sources responsible for the bulk of XRB energy density, confirming and extending results obtained from both deep and shallow surveys.
  - The combination of X-ray spectral analysis and deep VLT spectroscopy has revealed that  $\sim 10\%$  of high-redshift, high-luminosity objects optically classified as unobscured BL AGN are absorbed in the X-rays by column densities in excess than  $10^{22} \text{ cm}^{-2}$ .
  - The elusive properties of those AGN classified as X-ray Bright Optically Normal Galaxies (XBONG) can be due to a combination of the absorption associated with the AGN and the optical faintness of the nuclear emission with respect to the host galaxy. Obscuration of the nuclear source by large columns (possibly Compton thick) of cold gas seems to provide the most plausible explanation of the observed broad-band properties, though such a possibility is not unique.

The optical appearance of hard X-ray selected AGN is different from what expected on the basis of classic Unified Schemes, calling for some revisions to account for the discrepant classifications produced by the properties of the circumnuclear medium, and/or by geometrical or beaming effects (Chapter 2).

- Thanks to the large area covered, we have obtained the first spectroscopic identification of a sizable sample of objects with an extreme X-ray to optical flux ratio ( $X/O > 10$ ).

Different approaches, beside the photometric technique, to estimate the redshift of optically faint X-ray sources, have also been developed and tested to derive the redshift distribution of highly obscured, even Compton thick AGN:

- COLOUR-BASED REDSHIFTS: coupling the morphological information derived from K-band surface brightness profiles for a subsample of  $X/O > 10$  sources in the HELLAS2XMM survey, with the observed R-K colours, it was possible to derive a “minimum” redshift for these objects;
- A STATISTICAL APPROACH: on the basis of the optical to X-ray properties of identified sources it was possible to statistically assign luminosities — hence the redshifts — to optically faint X-ray sources in a combined sample of hard X-ray selected objects.
- THE DETECTION OF STRONG  $\text{FeK}\alpha$  FEATURES: it was possible to derive the redshift of highly obscured objects by detecting a strong  $\text{FeK}\alpha$  line in a few high S/N X-ray spectra of sources detected in the deepest *Chandra* fields.

A detailed comparison with X-ray selected sources in various deep and medium-deep surveys indicates that heavy ( $N_H > 10^{22} \text{ cm}^{-2}$ ) obscuration is almost ubiquitous among objects with high  $X/O$  and that obscured sources (in particular QSO2, the high-luminosity, high-redshift obscured AGNs predicted in XRB synthesis models) can be hosted in the bulge of luminous, massive ellipticals which already formed the bulk of their stars at high redshift (Chapter 3).

- Using the correlation observed between the  $X/O$  and the X-ray luminosity for obscured sources, it was possible to build a “virtually complete” sample of identified hard X-ray sources over a wide range of redshifts and luminosities. We have confirmed that a luminosity-dependent density evolution for the sources responsible for the XRB (low luminosity sources peaking at a later cosmic time) is needed to match the observed number and luminosity densities as a function of redshift. With this assumption, and the hypothesis that hard X-ray surveys probe the largest fraction of the whole AGN population, it is possible to explain the observed local BH mass density as entirely due to the growth of AGN (Chapter 4).

- The first comprehensive characterization of the X-ray properties of a large sample of X-ray detected EROs has been presented. Results obtained from a 80 ks XMM-*Newton* observation indicate that, at the relatively bright X-ray and near-infrared fluxes probed by the present observation, AGN contribute only for a negligible fraction ( $\sim 3\%$ ) to the optically selected EROs population. Although a spectroscopic redshift is not available for all of the sources, the X-ray, optical, and near-infrared properties of X-ray selected EROs nicely fit those expected for QSO2, confirming the results obtained in Chapter 3 from the HELLAS2XMM survey (Chapter 5).
- The results of *Chandra* stacking analysis of a well defined sample of spectroscopically identified, non-AGN EROs suggest that the dichotomy in the spectroscopic classification of the majority of K-selected, non-AGN EROs (e.g. dusty and old systems) appears to be present also in the X-rays: “dusty” objects are relatively bright X-ray sources ( $L_X \sim 10^{41} \text{ erg s}^{-1}$ ), while “old” EROs are below the detection threshold. Moreover, using the hard X-ray luminosity as a Star Formation Rate (SFR) indicator, it has been possible to estimate an average SFR for the dusty population in the range  $5\text{--}44 \text{ M}_\odot \text{ yr}^{-1}$ ; this estimate is lower than, although consistent with, the value based on the reddening-dependent [OII] emission and is in agreement with results from recent far-infrared and radio observations (Chapter 6).

Undoubtedly, the somewhat unexpected link between EROs and QSO2, is intriguing: near infrared observations of obscured QSO selected on the basis of their high X/O and, conversely, hard X-ray observations of a complete sample of EROs, constitute one of the strongest evidences that these two populations originally discovered at different wavelengths are intimately connected. **A selection criterion based on the X/O and the R-K colour of hard X-ray selected sources has been proposed, to efficiently pick-up the elusive QSO2 population**, difficult to select at optical wavelengths. Furthermore, X-ray detected EROs can be used as lighthouses to investigate the accretion paradigm at high redshifts to address the issue of elliptical galaxy formation and the expected co-evolution with the accreting black-holes.

## Future Directions

The description of the nature of hard X-ray selected sources has already approached a fairly complicate picture. While the general trends are rather robust (several independent arguments converge to the similar qualitative results) the number of X-ray sources with spectroscopic identifications is still far too small to derive accurate quantitative information about the AGN evolution at high redshift ( $z=2\text{--}4$ ). Moreover, in order to obtain robust estimates of the black hole mass density due to growth by accretion, a much better knowledge of the redshift, luminosity and Spectral Energy

Distributions (SEDs, related to  $k_{bol}$ ) of highly obscured AGN is of paramount importance.

The absorbed radiation emitted by the nucleus is expected to be re-emitted in the far-infrared and sub-mm bands. In this framework, *Spitzer* observations (from  $3.6 \mu\text{m}$  to  $170 \mu\text{m}$ ) of a well-selected sample of sources detected in the HELLAS2XMM 1dF sample (including XBONG, high X/O, EROs and QSO2) have been proposed, to complement the multiwavelength database and to probe the physical properties of those AGN for which the presence of SMBH is inferred from the X-ray emission but which remains elusive from observations at optical-UV and near-infrared wavelengths. Moreover, SCUBA ( $850 \mu\text{m}$ ) observations of an X-ray selected sample of X-ray Type II QSO could be crucial to derive a solid estimate of the bolometric luminosity of accretion powered hard X-ray sources and of the correlations between X-ray luminosity and obscuration with infrared emission.

The results from both deep and shallow surveys have unambiguously unveiled a differential evolution for the low- and high-luminosity AGN population. In this respect, the evolution of the obscured AGN luminosity function remains the key parameter to be determined. A study tackling simultaneously the problems of the shape and evolution of the luminosity function, and of the  $N_H$  distribution as a function of luminosity and cosmic epoch (with an approach akin to that followed by Ueda et al. 2003), will be the subject of future investigations (La Franca et al., in preparation).

The best strategy to properly address this issue is to increase the area covered in the X-ray band, and the corresponding optical-NIR photometric and spectroscopic follow-up, down to  $F_{2-10\text{keV}} = 1-5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ , where the bulk of the XRB is made, rather than pushing the depth of the survey beyond the present limits of the deepest *Chandra* surveys.

On the one hand, the optical follow-up of the HELLAS2XMM sources will be extended from 1 to  $4 \text{ deg}^2$ , in order to obtain a sample of 100-150 obscured objects at  $F_{2-10\text{keV}} > 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ , sufficient to constrain the high-luminosity tail of their X-ray luminosity function and to adequately figure their differential evolution over 2-3 luminosity dex and up to  $z \sim 2$  (Cocchia, PhD Thesis).

On the other hand, the XMM-*Newton* survey of the ELAIS-S1 field (Puccetti, PhD Thesis) will push the limiting fluxes down to  $2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$  over  $\sim 0.5 \text{ deg}^2$  allowing to considerably increase the statistic on high redshift, moderate luminosity objects.

Finally, a comprehensive multiwavelength program is underway to observe a contiguous area of  $\sim 2 \text{ deg}^2$  (the “COSMOS” project) using all the modern (HST/ACS, *Spitzer*, XMM-*Newton*, *Chandra*, VLT/VIMOS, VLA, GALEX) and future (e.g. ALMA) observatories from radio to X-rays. These data will provide the necessary photometry to characterize the SEDs of some thousands of AGNs as a function of redshift and type, and to explore almost all the aspects of galaxy/AGN evolution. The large area covered will allow a detailed comparison between galaxy and AGN clustering, and theoretical

models for the evolution of the large scale structure of the Universe. This will shed new light on the issue of whether AGNs trace higher density peaks or higher mass haloes in the high-redshift universe and how active sources are correlated with the environment.

With the full exploitation of all the multiwavelength data, it will be possible to build up large and homogeneously-selected samples of almost all the classes of objects revealed in the deep imaging surveys (e.g: AGN, EROs, B-dropout, High-z star-forming galaxies, cluster of galaxies etc.).

In particular, the combination of optical, near-infrared and X-ray (both *Chandra* and *XMM-Newton*) data of complete samples of EROs are crucial to definitively assess the fraction of reddened sources among the XRB constituents, the link between EROs, high X/O and QSO2, and the rôle of these objects in the framework of galaxy formation.